High current superconducting ampere class linacs (Contd.)

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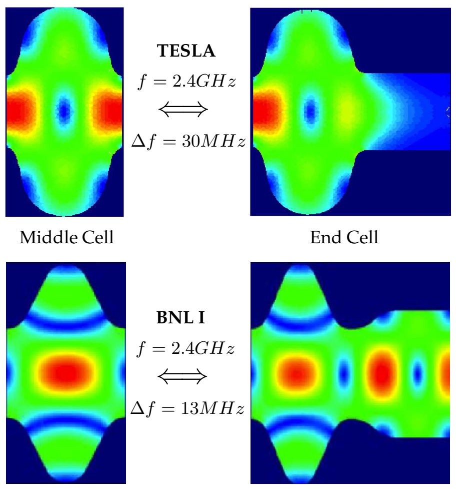
Higher Order Modes

The main causes of trapped modes are:

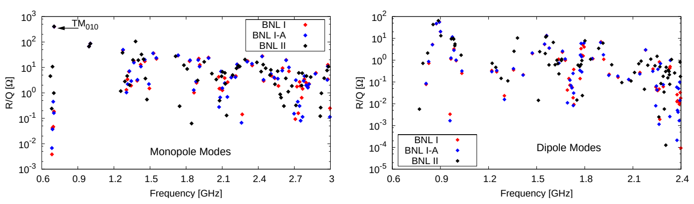
- Large number of cells
- Small irises resulting in small cell-to-cell coupling
- Difference in the end cell geometry from the middle cells. A simple example of an HOM in a TESLA cavity and BNL I cavity is shown below.



- HOMs below the cut-off frequency of the beam pipe. The beam pipe is enlarged to propagate all HOMs while staying sufficiently below the cutoff of the fundamental.

Shunt Impedance and Quality Factor

Fig. below shows a computation of the $R/Q's$ for monopole and dipole modes upto 2.5 GHz.



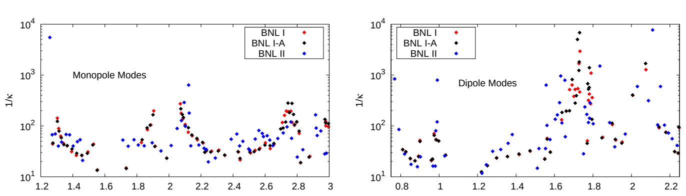
The Q of a mode is simply given by

$$Q = \frac{\omega U}{P}$$

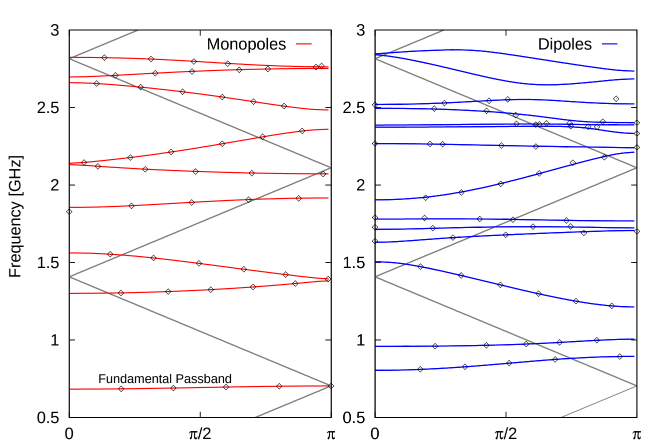
where ω is the frequency, U is the stored energy, and P is the power dissipated. For modes propagating through the beam tube, Q_{ext} (load) becomes the dominating factor. Frequency and time domain computational approaches are discussed and compared to measurements a on copper prototype.

HOMs: Frequency Domain

The influence of boundary conditions (BC) on the frequency can be used to infer the coupling of the mode to the beam pipe. Fig. below shows a comparison of coupling as a function of frequency for the three designs for both monopole and dipole HOMs. In the case of dipole modes, we see a few distinct bands with relatively higher values than the rest, but all modes are expected to propagate through the beam pipe.



where $L = \lambda\beta/2$ is the cell length, and ϕ is the phase advance per cell. The dispersion curves for a periodic structure (BNL I) along with the dispersion curves for the five-cell cavity is shown in Fig. below for both monopole and dipole modes. The solid black line represents the light cone ($f_\phi = \phi c/2\pi L$) folded into the phase region between 0 to π.

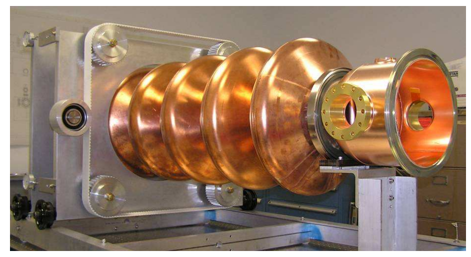


The beam strongly excites modes that are synchronous to the beam A flat dispersion curve may indicate to a potential trapped pass-band, and also make selective tuning of a single mode in the pass-band very difficult.

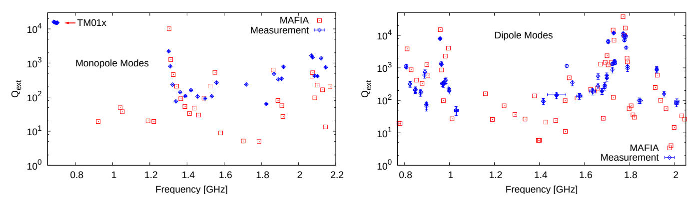
The most direct measure of a trapped HOM is to determine the external Q of the mode which also ultimately sets the thresholds for the onset of beam instabilities. The Q factor is given by

$$Q_{ext} = \frac{1}{2}\frac{Re(f)}{Im(f)}$$

Fig. below shows the prototype of the five-cell cavity used to measure the Q_{ext} of HOMs upto 2.2 GHz. The cavity is placed in a tuning fixture which is used to tune individual cells for frequency and field flatness.



A comparison of simulations and measurements of Q_{ext} for modes upto 2.2 GHz is shown Fig. below. These small Q_{ext} values are needed to raise instability thresholds to the ampere level and beyond.



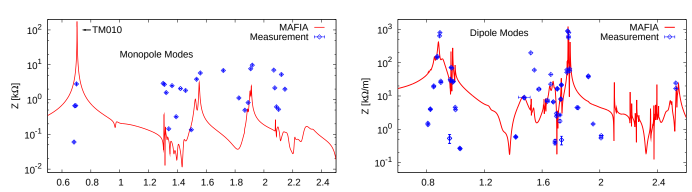
HOMs: Time Domain Method

In finite difference (or finite integration) time domain techniques allow one to simulate a real beam traversing any arbitrary structure and the possibility of an infinite waveguide. The broadband impedance spectrum can be directly obtained from a Fourier transform of the wake potential normalized by the bunch spectrum $\rho(\omega)$ which is given by

$$Z_{||}(\omega) = \frac{1}{c\rho(\omega)}\int_{-\infty}^{\infty} W_{||}(\vec{r},s)e^{-i\frac{\omega}{c}s}ds$$

$$Z_{\perp}(\omega) = -\frac{i}{c\rho(\omega)}\int_{-\infty}^{\infty} W_{\perp}(\vec{r},s)e^{-i\frac{\omega}{c}s}ds$$

Fig. below shows broadband impedance spectrum of longitudinal and transverse modes computed by time domain methods and compared to measurements performed on the copper prototype.



The external Q factors are smaller than the 10^4 and are sufficiently damped to suppress both single bunch and multibunch effects which follows.

Single Bunch Effects

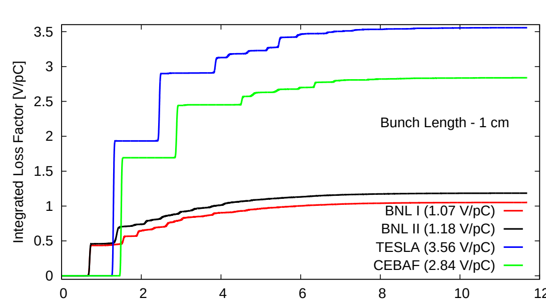
For a Gaussian bunch of RMS length σ_z, the power lost in the accelerating structure can be expressed as

$$P_{lost} = k_{||}q_b^2 f_b$$

where q_b is the bunch charge, f_b is the beam repetition frequency, and $k_{||}$ is the longitudinal loss factor which is given by

$$k_{||}(\sigma) = \frac{1}{2\pi}\int_{-\infty}^{\infty} Z_{||}(\omega)f(\omega,\sigma)d\omega$$

where $f(\omega,\sigma) \approx e^{-\omega^2\sigma^2}$ is the spectral power density of a Gaussian bunch. The loss factor was calculated using ABCI [?], for a Gaussian bunch of RMS length of 1 cm traveling through the cavity for BNL, TELSA and CEBAF designs.

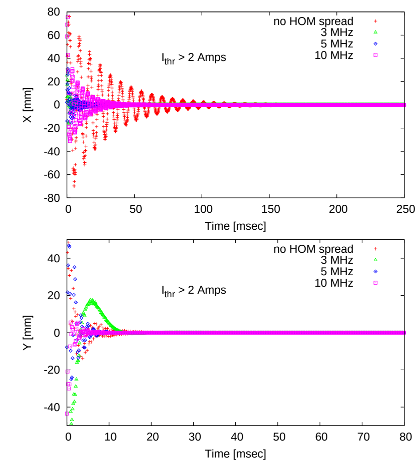


The integrated loss factors and the corresponding power dissipated for electron cooling scenario with 5 nC bunch charge and 50 mA beam current are listed in Table below. Estimates for the energy spread and the emittance growth induced by the corresponding accelerating structures are shown in Table below for nominal bunch length ($\sigma = 1\ cm$) and bunch charge ($Q = 5\ nC$) and are....

Parameter	Unit	BNL I (HC)	BNL II (HC)	CEBAF(HG)	TESLA(HG)
$k_{\|\|}\ (\sigma_z - 1cm)$	[V/pC]	4.25	10.71	13.14	13.14
$k_{\perp}\ (\sigma_z - 1cm)$	[V/pC/m]	3.22	2.24	2.07	2.07
$\delta E/E\ (Q - 10nC)$	-	?? %	?? %	?? %	?? %
$\Delta(\gamma\epsilon)/\epsilon_0\ (Q - 10nC)$	-	?? %	?? %	?? %	?? %

Multibunch Instabilities

If the bunch returns back "in-phase" with the excited HOM, it can form a closed feedback loop between the beam and cavity. If the Q_{ext} is sufficiently large, the induced voltage in the HOM grows exponentially and lead to multibunch beam breakup. Simulations were performed for an electron cooling scenario shown in Fig. below no growth of multibunch BBU with a unit recirculating transfer matrix.



Power Coupler Kick

The presence of single FPC can lead to a non-zero transverse field on-axis resulting in a kick to a bunch traversing the structure. The transverse fields for the case of a single coupler with and without a symmetrizing stub and a symmetric coupler with a 1 mm relative offset is shown in Fig. below

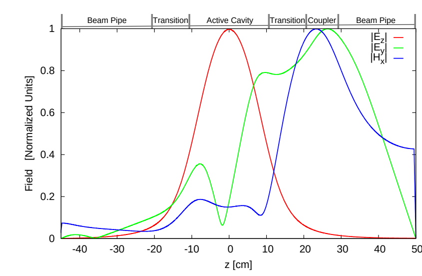
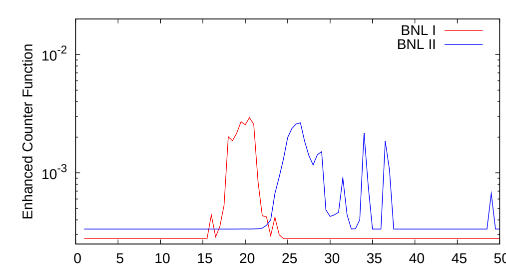


Table below shows the kick factors, transverse kicks, and the corresponding emittance growth for three cases with transverse RF fields.

Scheme	$\delta_t \times 10^{-4}$	Kick	$d\epsilon/\epsilon$
Single Coupler	(-9.3 + 1.2i)	0.85 mrad	
Single Coupler + Stub	(3.0 - 3.8i)	0.27 mrad	
Dual Couplers	(0.6 - 0.6i) mm^{-1}	50 μrad	

Multipacting

The total number of electrons after a given number of impacts normalized to the average secondary emission coefficient corresponding to the impact energy (enhanced counter function) is shown in below as a function of peak electric field. No hard multipacting barrier is expected since the onset of multipacting requires the ECF to be greater than one.

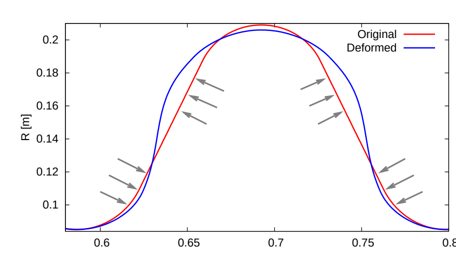


Lorentz Force Detuning

The radiation pressure due to Lorentz force is given by

$$P_{rad} = \frac{1}{4}\mu_0\vec{H}^2 - \epsilon_0\vec{E}^2$$

Fig. below shows the effect of radiation pressure on the cavity shape for an $E_{acc} = 1\ MV/m$ with a wall thickness of 3 mm. The Young's modulus and the Poisson's ratio were taken to be 103 GPa and 0.38 respectively.



K_L for the BNL I cavity was calculated to be $1.28Hz/(MV/m)^2$.

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